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STUDIES FOR STUDENTS

THE STRUCTURE OF METEORITES. II.

(Continued from page 66)

CHONDRITIC STRUCTURE

This characterizes the great majority of stony meteorites, and being peculiar to meteorites will be described in detail. Of the 314 stone meteorites listed by Wülfing in his recent classification, 288 are more or less largely composed of chondri. Some meteorites are composed of chondri almost exclusively (Borkut) while others contain them imbedded in a groundmass. The latter may be tuffaceous, glassy or crystalline. The term chondrus, plural chondri, is from the Greek *χόνδρος*, a grain, the term being applied in reference to the size and shape of the body. Some writers prefer the diminutive form of the word, viz.: chondrules. In size chondri may vary from that of a walnut to a dust-like minuteness. The larger number are about the size of millet seeds. The form of chondri is generally spheroidal, but varies from essentially spherical to mere irregular fragments. Some chondri are flattened or oval and others show apparent deformation subsequent to their origin. In the latter, depressions or projections occur which often look as if a hard chondrus had pressed against another soft one during the process of formation. The deformed chondri pass by every gradation into those which appear to be rock fragments with rounded angles. The surface of the chondrus is rarely smooth, being usually rough or knobbed. From many friable meteorites individual chondri can easily be isolated, but if the meteorite is at all coherent the chondri break with the rest of the mass. The color of chondri is usually white or gray, but some are brown to black. As they are often of the same ingredients as the groundmass in which they are imbedded they may differ little in color from it. On this account and on account of an ill-defined contour they may be overlooked and a crystal may be considered porphyritic, which is really part of a chondrus. Usually, however, the chondri are plainly marked on a polished section by differences in color and contour. In structure chondri may themselves be granular, porphyritic, coarsely or finely fibrous. They may consist of a single crystal individual, in which case they are said to be monosomatic, or of several individuals, when they are said to be polysomatic.

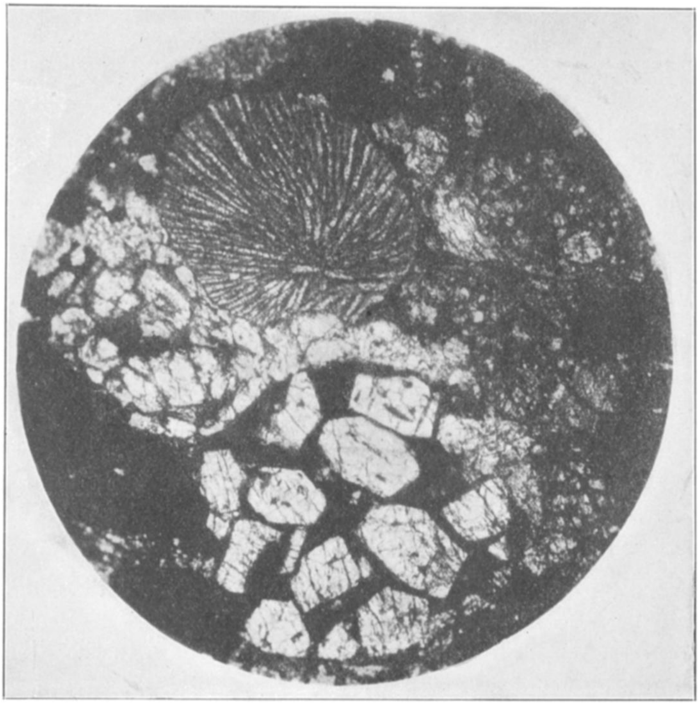

FIG. 7.—Section of the Homestead meteorite, showing a typical eccentrically-radiating bronzite chondrus (above) and a porphyritic chrysolite chondrus (below). A granular chrysolite chondrus also appears at the left. × 65. After Tschermak.[1]

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[1] Die mikroskopische Beschaffenheit der Meteoriten. Tafel VII, Fig. 4. Figs. 2, 3, 4 and 5 of Article I should also be credited to Tschermak, Lehrbuch der Mineralogie, 4th edition, p. 585.

True monosomatic chondri are confined almost exclusively to the mineral chrysolite. They can be known by their simultaneous extinction in polarized light. Polysomatic chondri may be made up of different minerals as well as different individuals and may show more than one kind of structure, *i. e.*, a chondrus may be granular in one portion and fibrous in another. The following minerals are noted by Tschermak as forming chondri, their relative abundance being in the order named: Chrysolite, bronzite augite, plagioclase, glass, and nickel-iron. This order, it is to be noted, is also that of the fusibility of the minerals, the most infusible and hence the earliest cooling mineral forming the most chondri. Chrysolite chondri usually contain large quantities of glass of a dark brown color. This may be arranged (*a*) in the form of alternating layers, in which case a marked rod-like or lamelliform appearance is produced, or (*b*) may form a base in which the mineral is developed porphyritically, or (*c*) may occur in the center of a crystal, or (*d*) may form a network. Polysomatic chondri of the latter sort are especially liable to be mistaken for those of bronzite since they simulate the fibrous appearance of the latter. Occasionally the crystallization may have proceeded only far enough to produce skeletal or branching growths of the mineral among the glass. Both monosomatic and polysomatic chrysolite chondri may have the arrangement of a well-marked rim about a spherical interior. This rim may, in the polysomatic chondri, be composed of many individuals. Such a rim is often dark from a content of iron and troilite. Chromite, either in minute grains or in dust-like aggregations, also forms a common inclusion usually near the surface of the chondrus. The quantity of opaque inclusions may be so great as to give the chondrus a black color. Such chondri associated with those of light color are to be found in the stones of Knyahinya, Mezo-Madaras and others. The constituent minerals of such chondri are chiefly chrysolite and bronzite. Bronzite chondri are usually of a finely fibrous character. The fibers instead of radiating from a center as do those of spherulites usually radiate from an eccentric point. This eccentric arrangement constitutes one of the most marked features of the chondri and separates them sharply from any formation seen in terrestrial rocks. The bronzite chondri have less glass than those of chrysolite. Monosomatic chondri of bronzite have never been observed, the large crystal individuals showing, as a rule, no tendency to a spherical form. Besides bronzite chondri having an eccentric arrangement of fibers there occur those which are confusedly fibrous, and these may pass into those which have a netted appearace from crossing fibers. Such chondri, cut at right angles to the fibers, show the fibers to have a concentric arrangement. The

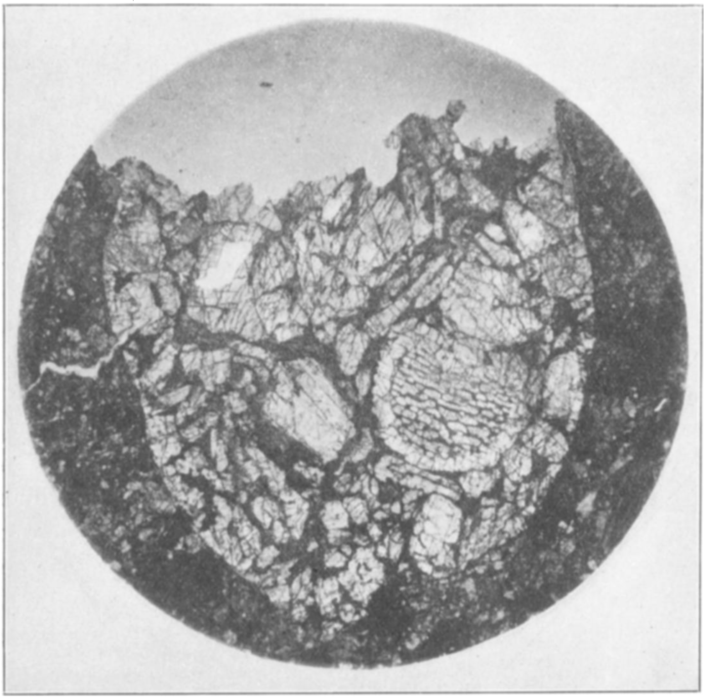

FIG. 8.—Section of the Dhurmsala meteorite, showing a large, somewhat porphyritic chondrus enclosing a smaller monosomatic one. Both are composed of chrysolite. × 8. After Tschermak.[1]

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[1] Op. cit. Tafel VIII, Fig. 1.

chondri already mentioned, which are granular in part and in part fibrous, are usually made up of the two minerals chrysolite and bronzite. These minerals may be present in about equal quantity or either may be in excess. Usually the bronzite together with glass appears to occupy the intervening spaces between the chrysolite grains, indicating that it is of later formation. Augite chondri are not common but occasionally occur. They often show a structure which indicates repeated twinning. The mineral may appear also in the form of grains, usually of a green color. These grains can be distinguished from chrysolite by their behavior in polarized light. Chondri containing plagioclase in any large quantity are also rare but have been observed by Tschermak in the stone of Dhurmsala. The plagioclase alternates in bands with chrysolite and is in excess. Chondri also occur which are composed almost exclusively of glass, the only indication of the presence of other minerals being in the presence of forked microlites which may be referred to bronzite. Occasionally these microlites are of a pronounced star-like form. Chondri, or at least rounded spheres of nickel-iron, occur in some meteorites, though they are not common. All gradations occur from chondri which contain grains of nickel-iron to complete spheres of nickel-iron. In the stone of Renazzo such spheres have a covering of brown glass. Some of the spheres or rounded fragments also contain troilite, but troilite of itself never has been seen to form chondri. A more or less complete rim of metal is a characteristic of many chondri. The metal may occur in the form of rounded grains or as a continuous periphery. It has been suggested by Daubrée that such a rim shows that the chondrus has been subject to the reducing action of hydrogen. Besides the chondri colored black by inclusions of iron and troilite, as previously described, black chondri, which consist chiefly of maskelynite or granular plagioclase, occur in the stones of Alfianello, Chateau Renard and others. These chondri are transparent and colorless about their rim, but in the interior are totally black from inclusions of angular rounded grains, some of which are shown by their brown color to be troilite. A gathering of grains at the center distinguishes these chondri from those previously described in which the rim was black. Besides complete chondri, fragments representing various proportions of a complete chondrus occur. These may, on account of their shape, be very misleading, as they may be taken for porphyritic individuals or for portions of a foreign stone if their previous chondritic origin is not recognized. Tschermak states that fragments of chondri are most numerous in the stones whose chondri have well-marked contours. So far as the association of chondri is concerned it is to be noted that chondri of more

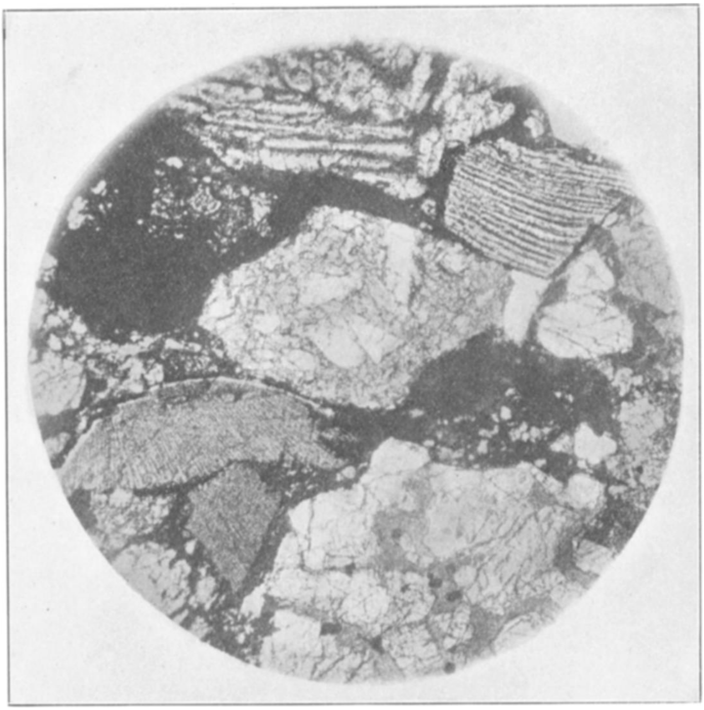

FIG. 9.—Section of the Mezo-Madaras meteorite, showing a meteoritic tuff made up of fragments of chondri. Portions of bronzite, chrysolite and nickel-iron chondri can be recognized. After Tschermak.[1]

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[1] Op. cit. Tafel XIX, Fig. 4.

than one of the kinds above described usually occur promiscuously scattered through the same stone. There is no gathering of them into groups according to the minerals they contain. Occasionally one chondrus encloses another, and still more rarely two may be joined together. Broken fragments of chondri commonly occur in the same stone with complete chondri. Two fragments of the same chondrus are, however, rarely if ever found in juxtaposition. Hence there must have been considerable separation of the fragments before consolidation of the stone took place.

Theories of the Origin of Chondri and Chondritic Structures.--The conditions which have brought about the formation of chondri are not well understood, though the question has been much discussed and various hypotheses have been suggested. The views of earlier observers were to the effect that the chondri represented fragments of preëxisting rock which, by oscillation and consequent attrition, obtained a spherical form. Sorby regarded them as produced by cooling and aggregation of minute drops of melted stony matter. Tschermak considers their origin similar to that of the spherules met with in volcanic tuffs which owe their form to prolonged explosive activity in a volcanic throat breaking up the older rocks and rounding the particles by constant attrition.

Different views are, however, held by Brezina, Wadsworth, and others, these believing that the chondri have been produced by rapid and arrested crystallization in a molten mass.

Objections to theories of the first class are to be found (1) in the fact that the chondri usually have rough-knobbed surfaces instead of smooth ones, such as attrition might be expected to produce; (2) in the regularly eccentric form of most enstatite chondri, which attrition would be likely to destroy; and (3) in the fact that fragments of a preëxisting rock ought to show the constitution of the rock as a whole instead of specialized structure. Objections to theories of the second class are to be found chiefly in the clearly fragmental nature of most chondritic meteorites. It is in their variation from the surrounding ground mass and in the eccentric arrangement of their fibers that chondri differ chiefly from the spherulites of terrestrial rocks.

SUPERINDUCED STRUCTURES

Several structures occur in meteorites which have apparently originated subsequent to the consolidation and solidification of the mass as a whole. These may be enumerated as (1) slickensides, (2) faults, (3), bent plates, (4) veins, and (5) cleavage and joints. The first three may be grouped under the head of evidences of preterrestrial movement, but it should be stated that some authorities regard all these structures, including veins, as of terrestrial origin.

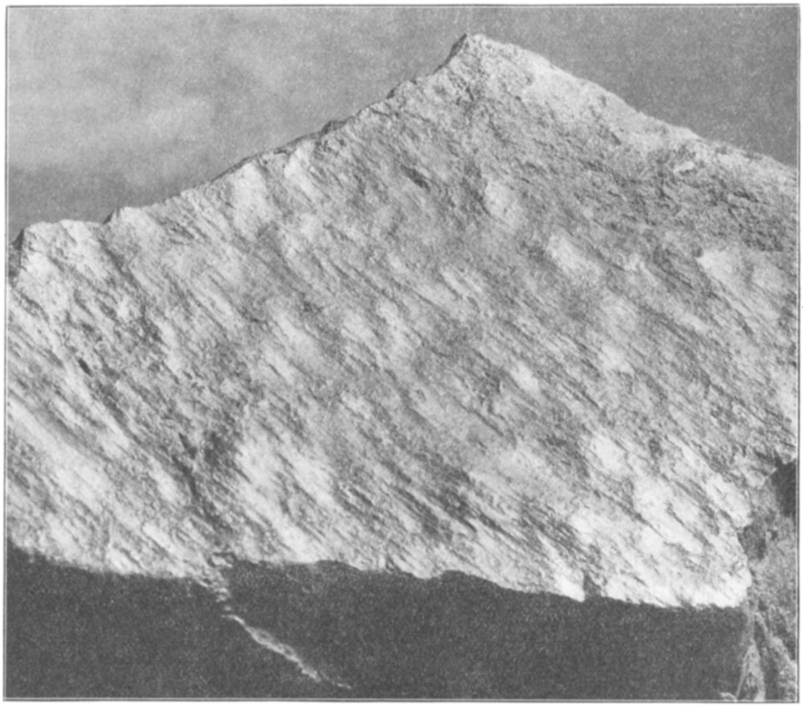

FIG. 10.—Slickensided surface, Long Island meteorite. Natural size. From a specimen in the Field Columbian Museum.

Slickensides (*Harnisch flachen, Surfaces de frottement.*)—These may be observed on portions of many meteorites, of which the following may be mentioned among others: Bath, Kesen, Limerick, Lixna, Long Island, Manbhoom, Mocs, Ochansk, Ställdalen, Tysnes Island, and Zavid. The slickensided surfaces may vary in area from a few square millimeters to those more than a foot square (Long Island). In many cases the surfaces have exactly the appearance of similar ones in terrestrial rocks, being smooth, shining, somewhat uneven, and more or less striated in the direction of movement. In other cases, however, they appear as dark striations on the contact surfaces, or as if the surfaces had been rubbed with a piece of graphite. The slickensided surface may be a broad peneplane with generally parallel striae, or it may be seen penetrating the meteorite in numerous narrow peneplanes following the same general directon at different levels. The surfaces do not always extend in the same direction, however, but in different directions and occasionally nearly at right angles to one another. One surface on the Long Island meteorite has in cross section the shape of a J. The polishing of the surface by the movement which has taken place often brightens the metallic grains so that they shine. Sections cut perpendicular to a slickensided surface show a flattening or elongation of the metallic grains, and even of other minerals along the course of movement,

Meunier regards the blackening seen on the surfaces as indicating heat developed by the movement, and states that the heat was sufficient to metamorphose a portion of the Mexico meteorite included between two slickensided surfaces, which he examined. The slickensided surfaces examined by the writer, however, give no evidence that the movement has been accompanied by any high degree of heat, at least enough to produce fusion, for the mineral grains along the surface are simply sharply cut off without alteration. This fact, together with the analogies given by terrestrial slickensides, indicate that the movements which gave rise to the slickensides must have taken place while the constituents of the rock were solid.

Faults.—Evidence of movement along a plane sufficient to produce well-marked faults in meteorites is not abundant. The slickensides already described prove slight movement, but how much, so far as the stony meteorites are concerned, it is difficult to say on account of the absence of bedding planes and other criteria of measurement. In the iron meteorites, however, the bands of the Widmanstätten figures afford a means of measurement. Sections of several such meteorites, viz., Bridgewater, Carlton, Magura, Puquios, and Descubridora, in this way exhibit faulting. In the Puquios meteorite the faulting is of somewhat complicated character, the kamacite bands showing slight dislocation in various directions. The largest fault extends the entire length of the mass, and has a throw of ⅛ of an inch (3 mm). Some crushing and branching also appears along this line of faulting. Other less extensive lines of faulting occur. The amount of throw seen in the Descubridora meteorite is more extensive than in the Puquios, being a distance of from ¼ to ½ an inch (6 to 12 mm). Owing to the toughness and tenacity of iron meteorites at ordinary temperatures, Howell has suggested that such faulting could only have been produced when the mass was highly heated, as, for instance, in its passage near the sun. He found that a piece of the Toluca meteorite, although very tough when cold, would crumble under the hammer when heated to a white heat. He states that it also seems necessary to assume a contact with some other body, as well as a heating, in order to account for the faults. In opposition to this view by Howell the faulting is believed by Brezina, according to a label in the Vienna Museum, to have been the result of the impact of the mass on the earth.

Bent plates.—These are somewhat allied to faults, there having been differential motion in the mass, but not a sufficient amount to produce fracture. Naturally, they are to be noted only in the iron meteorites. Carlton, Glorieta Mountain, Jamestown, Ranchito, and Toluca are some of the meteorites in which they have been observed. The bent plates appear upon an etched surface as curved Widmanstätten figures. They never characterize an entire mass, so far as I am aware, but only portions, and occasionally but a small portion of a single mass. The amount of curvature is not great, rarely if ever exceeding 19^{mm} in 50. A single plate never has more than one direction of curvature, though it is often straight for some distance at one end and curved at the other. With reference to each other, however, the directions of curvature of individual plates may be quite different. Like faults, the bending is referred by Brezina to the result of the impact of the meteorite upon the earth.

Veins (*Adern*, *Filons*, *Veines*).—These occur in many stony meteorites, in fact in a sufficient number to characterize seven of the thirty-seven groups into which Brezina divides stony meteorites. The veins may vary in width from a mere line to 19 millimeters (Mocs). An even greater dimension is indicated by the size of single stones from the Pultusk and Mocs showers, which seem to be of a substance like that of the veins. The veins penetrate the stones now in a nearly straight direction and now in a more or less tortuous one. Sometimes they are single, then again branched, and again ramify to such an extent as to form a network. They are rarely uniform in width for any appreciable distance. On the contrary, they widen and narrow very irregularly, often forking so as to enclose portions of the mass and then meeting again. The Bluff meteorite shows two systems of veins crossing one another at angles of about 45°. The narrower of these is uniform in width and was observed over a plane 4 × 15 inches in extent. The wider varies much in width and is less extensive.

In color, veins are dark, usually black. The substance filling them is black, opaque, brittle, and of a semi-glassy character. In polarized light it appears amorphous and isotropic. It often includes splinters of the adjoining stone and little spheres of nickel-iron and troilite. Along the walls are often seen delicate metallic foliae, lying parallel to the direction of the veins. These appear in cross section like delicate threads. From the nickel-iron grains threads often run out in a direction across that of the vein, and these may pass into empty clefts. In many portions of the stone of Chantonnay narrow, irregular, open fissures occur. Some of these have begun to be filled by matter that has flowed in from the surface, but it has penetrated only to a depth of a few millimeters. The vein substance usually has fairly well-defined walls, but on the other hand may gradually pass into the body of the meteorite. In the stone of Goalpara, which is coarsely porous, a black, vein-like substance forms the walls of the pores, makes up the groundmass, and

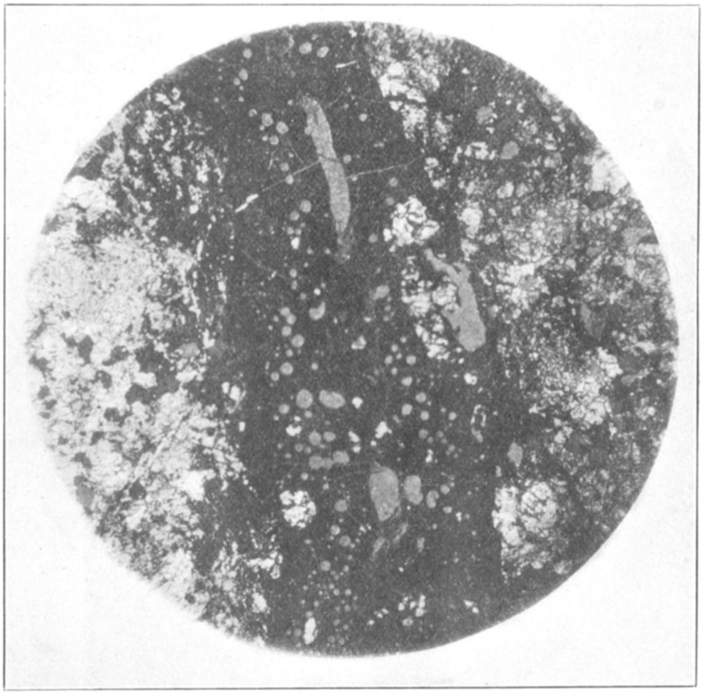

FIG. 11.—Cross section of a vein of one of the Mocs meteorites. The vein mass appears as a broad black band through the center. It is in part intermixed with the adjoining groundmass and in part has well defined walls. The gray spots are spheres and lumps of nickel-iron illuminated by reflected light. The branching of some of these into clefts, one of which is still open, is of interest. × 20. After Tschermak.[1]

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[1] Op. cit. Tafel XXII, Fig. 2.

penetrates into the minutest fissures. Again, the groundmass of the stone of Richmond is a black, half glassy substance which occupies the spaces between the chondri and spreads itself into their interstices. Thus the veins may occur as mere apophyses of a black groundmass. In fact, apparently the same substance forms veins in the meteorites of Mocs, a cement in the stone of Orvinio, and the entire groundmass of such carbonaceous meteorites as Cold Bokkeveld. That the substance is exactly the same in all these cases cannot be regarded altogether proved as yet, however. An analysis by Whitfield of the vein substance of the Bluff meteorite showed it to be very similar in composition to the mass of the stone. Tschermak states that the vein substance of the Goalpara stone consists of a network of iron, holding troilite, carbon, and a glassy substance found to be decomposed by acids. The substance of the black veins of the Chantonnay meteorite Meunier regards as consisting of a silicate of iron. An interesting experiment performed by him in this connection was that of heating meteorites of the group to which he gives the name of Aumalite, to redness without access of air. The meteorite then became black, of lighter specific gravity, and increased in hardness and toughness. In other words, it became a substance which he regards as exactly similar to that of the veins of Chantonnay. He regards the presence of this substance in the stone of Chantonnay, therefore, as proof that the meteorite had undergone heating or metamorphism before its entrance into the earth's atmosphere.

So far as the general appearance of the black veins is concerned, it may be said with Tschermak that they give the impression that the substance of the meteorite at some time underwent fissuring and that a fused liquid was absorbed into these fissures. The phenomenon must have differed somewhat from that of the injection of fused lava into the interstices of terrestrial rocks, since the substance of the vein mass agrees so closely in composition with that of the substance of the meteorite.

Vein-like filaments.—In passing from the iron to the stony meteorites every gradation may be traced from metallic masses in which the silicates appear as porphyritic ingredients, through those appearing to be made up of interwoven constituents, to those in which the metallic constituents appear as isolated grains. In several of the latter class of meteorites (Farmington, Crab Orchard Mountains, Bluff) long, branching, metal filaments are seen to be associated with the isolated grains.

In the view of the present writer, these are filamentous phases of the structure of the metallic portions of the meteorite. Other meteorites, of which those of Honolulu, Mocs, and Pultusk may serve as illustrations, have what appear to be metallic veins when seen in cross sections. When cleft along the vein, however, these prove to be slickensided surfaces along which the metallic grains of the meteorite have been drawn or flattened out by the movement. These vein-like structures are clearly of different character from those just described. They sometimes give a well-marked appearance of a vein outlined on the crusted surface of a meteorite. This is owing to the fact that resisting fusion more than the stony matter they stand out in relief.

Cleavage and joints.— Most of the cubic irons are characterized by a complete cubic cleavage. This cleavage doubtless indicates that the masses are crystal individuals. Huntington has described cleavage planes as passing through some of the octahedral irons independent of the octahedral structure. It is probable that these, as well as cleavage along the octahedral planes often noted, are separation planes resulting from weathering.

Few stone meteorites are of sufficent size to exhibit a jointed structure if it existed. Meunier has called attention to an elongated depression in one of the L'Aigle stones which he regards as marking the position of a former joint plane. The Long Island meteorite, the largest stone meteorite known, is cut by three large division planes which perhaps represent joint planes. Two of them are at right angles to one another, while the third, somewhat broken, is nearly at right angles to the other two. The great irregularity of form of most meteorites, however, would seem to indicate that division planes were lacking in the masses from which they have separated.

SYNTHETIC EXPERIMENTS IN THE REPRODUCTION OF STRUCTURAL DETAILS

Fouqué and Levy have succeeded in reproducing, so far as the component minerals were concerned, mineral aggregates corresponding to several types of meteorites. Among meteorites not containing feldspar, aggregates were produced corresponding to the meteorite of Rittersgrün, which is made up of chrysolite, enstatite, a magnesian pyroxene, and iron. Among meteorites containing feldspar, aggregates were produced corresponding to those of the class known as Eukrites, which are made up of anorthite, enstatite, and pyroxene, and of the class made up of anorthite, enstatite, and chrysolite. These were all produced by cooling from fusion, different mixtures of silica, alumina, magnesia, carbonate of lime and iron oxide. The chief difference noted by these authors between these products and meteorites of corresponding chemical composition is one of structure. The artificial products were of a marked granitoid texture, while most meteorites have as strongly brecciated or tuffaceous character. It is also true that the iron in the artificial products was in the form of oxide. This could, however, easily be reduced to the metallic state by exposing the mass to the action of reducing gas at a red heat for two hours. Previous to the experiments of Fouqué and Levy stone meteorites of several types had been fused by Daubrée and the resulting cooled products examined. The products resembled the original masses in some respects, but in many respects differed. Thus chrysolite and enstatite separated in a sort of liquation, the chrysolite forming a thin layer above, while the enstatite crystallized below in the form of long needles. Moreover the iron grains took spherical forms rather than the irregular ones which characterize meteorites. Daubrée therefore concluded that the mode of formation of meteorites differed from purely igneous fusion. The needles of enstatite artificially obtained seemed analogous in his opinion to the needles formed on the surface of freezing liquids, while the grains seen in meteorites seem more like the forms of frost or snow formed by the immediate passage of water vapor to the solid state. This conclusion led to a number of experiments by Meunier with vapors of silica, magnesia, etc., for the purpose of forming in this manner if possible mineral aggregates resembling the meteorites The results so far obtained have been chiefly negative, though the experiments are still being conducted. A prominent feature lacking from the results of the experiments with vapors is the glass so abundant in meteorites. This is obtained in quantity however in the products cooled from fusion.

Many efforts have been made to reproduce Widmanstätten figures but they cannot be said to have met with much success. As it is held that the Widmanstätten figures indicate slow cooling from fusion, Sorby fused together iron, nickel, and other constituents of an iron meteorite, and allowed the mass to cool very slowly. On examining an etched surface with a lens, minute lines were seen which recalled the Widmanstätten figures but the appearance as a whole, he states, was very different. The mass was then kept for a long time at a temperature just below that of fusion but the resulting product was less like meteoric iron than that previously obtained. Daubrée fused a portion of the Caille meteorite in a crucible of clay, then allowed the mass to cool slowly. The resultant mass showed a crystalline structure but all trace of the former Widmanstätten figures was lost. On fusing a mixture of iron, nickel, troilite, and silica, he obtained a product showing dendritic figures. On fusing a mass of iron, nickel, and iron phosphate together, a mass having a reticulated structure with angles showing dodecahedral crystallization was obtained, The structure of this mass approached more nearly the Widmanstätten figures than any obtained in any other way, and it is sometimes stated that true Widmanstätten figures were produced. As Cohen remarks, however, the statement needs to be supported by figures and specimens. The same may be said of Meunier's statement that he found Widmanstätten figures on a mass obtained by reducing iron and nickel chlorides from their vapors. J. Lawrence Smith states that he obtained Widmanstätten figures on a button of iron which cupelled from a mixture of iron silicate and chalk heated to fusion for from 15 to 20 minutes in oxygen in excess. If the excess of oxygen was essential to the success of this experiment, it was a condition certainly wanting in the formation of the iron meteorites.

It is true of chondri as of Widmanstätten figures that they have not yet been successfully reproduced by synthetic methods. Especially has it been found impossible to reproduce the structure exhibited by many enstatite chondri, of fibers radiating from a point eccentrically placed with reference to the center. Meunier has obtained from vapors of silicon chloride and magnesium acicular crystals of pyroxene which he recently showed the writer, which radiate in a fashion recalling the above-mentioned chondri. They cannot, however, be said to be in any sense reproductions of the chondri, and they are moreover a monoclinic pyroxene. Perhaps the nearest approach in form to these structures has been obtained recently by Brauns in crystals obtained by cooling sulphur. The forms were produced either by suddenly cooling a strongly heated preparation of sulphur or by slowly cooling and suddenly shaking it. Such results suggest that the peculiar structures of chondri indicate special conditions of cooling or percussion to which the mass has been subjected. If these conditions could be reproduced, chondri could, perhaps, be formed synthetically. It may be suggested that immediate contact with the intense cold of space, a condition which has not yet been experimentally fulfilled, is perhaps the force which has given chondri their peculiar form.

NOTE.—For further study and for lists of references the following works may be consulted: Meteoritenkunde, Heft I, E. COHEN, Encyclopedie chimique, Tome II, Meteorites, S. MEUNIER ; Die mikroskopische Beschaffenheit der meteoriten, G. TSCHERMAK.

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